Ground Improvement
Volume 168 Issue GI1

Optimisation of coal wash–slag blend as a structural fill
Chiaro, Indraratna, Tasalloti and Rujikiatkamjorn

ice | proceedings

Proceedings of the Institution of Civil Engineers
Ground Improvement 168 February 2015 Issue GI1
Pages 33–44 http://dx.doi.org/10.1680/grim.13.00050
Paper 1300050
Received 15/08/2013 Accepted 30/09/2013
Published online 14/01/2014
Keywords: geotechnical engineering/land reclamation/recycling and reuse of materials

ice
Institution of Civil Engineers
publishing

Optimisation of coal wash–slag blend as a structural fill

1 **Gabriele Chiaro** MSc, PhD
Research Fellow, Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong, NSW, Australia

2 **Buddhima Indraratna** MSc, DIC, PhD, FTSE, FIEAust, FASCE, FGS
Professor of Civil Engineering, School of Mining and Environmental Engineering, Research Director of Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong, NSW, Australia

3 **S. M. Ali Tasalloti** MSc
PhD Candidate, School of Civil, Mining and Environmental Engineering, University of Wollongong, Wollongong, NSW, Australia

4 **Cholachat Rujikiatkamjorn** BEng (Hons), MEng (AIT), PhD
Associate Professor, Centre for Geomechanics and Railway Engineering, University of Wollongong, Wollongong City, NSW, Australia

Coal wash (CW) and basic oxygen steel slag fines (BOS) are by-products of the coal mining and steel industries, respectively. Their effective reuse and recycling through large-scale geotechnical projects, such as port reclamation, is economically beneficial and environmentally sustainable. In this study, CW and BOS were blended in order to explore the possibility to obtain synthetic fills having geotechnical properties similar or superior to conventional fills, therefore suitable as a structural fill for the Port Kembla Outer Harbour reclamation near Wollongong City, Australia. A framework with four levels of acceptance is proposed in this paper to select granular waste as structural fill materials. This framework was used for optimising the CW-BOS blend. It was found that for the Port Kembla Outer Harbour reclamation, a CW-BOS blend with a BOS content between 30 and 45% can meet most geotechnical specifications (i.e. high shear strength and bearing capacity, low swelling and particle breakage levels, and adequate permeability) required for a suitable structural fill above the high tidal level.

1. Introduction

Located on the east coast of Australia, Wollongong's Port Kembla is one of three major ports in the state of New South Wales (NSW), the others being Sydney and Newcastle. The Port Kembla Harbour was established in the late 1890s to facilitate the export of coal from the mines of the Wollongong region. Since that time it has rapidly grown to accommodate both the expansion of traditional industries along with the development of new ones. Port Kembla Port Corporation (PKPC) is currently expanding its outer harbour (Figure 1) to provide additional land and berthing facilities to cater for future trade growth. Whereas the recent inner harbour development provides facilities to cater for the growth of existing trades, the outer harbour development has the potential to address the needs of new industry. It includes the reclamation of approximately 42 ha of land and the construction of seven new berths (Lai *et al.*, 2011).

For the above-mentioned project, the Centre for Geomechanics and Railway Engineering of the University of Wollongong was requested to explore the use of coal wash (CW) and basic oxygen steel slag fines (BOS) mixtures as potential reclamation fills, as an economical alternative to the conventional (quarried) aggregates and dredged sandy fills. CW and BOS are typically considered as waste materials from the coal mining and steel making industries, and disposed of in stockpiles occupying usable land in urban areas. At present, in the Wollongong region, these granular wastes are produced at an annual rate exceeding 2 mt. Their effective reuse and recycling through large-volume civil engineering applications, such as port reclamation and/or for use as backfill materials, is vital for the local economy and environmental sustainability.

Well-compacted natural granular materials (e.g. sands and gravels) generally satisfy the geotechnical design specifications of structural fills (i.e. in terms of shear strength, bearing capacity and permeability). Nevertheless, this is not always the case with industrial granular wastes, especially CW (Okabue and Ochulor, 2007; Rujikiatkamjorn *et al.*, 2013). The recent preliminary testing conducted by the authors indicated that properly compacted CW has a good potential as a general fill for small embankments, but is not appropriate as a structural fill for bearing significant loads. It is expected that its frictional strength

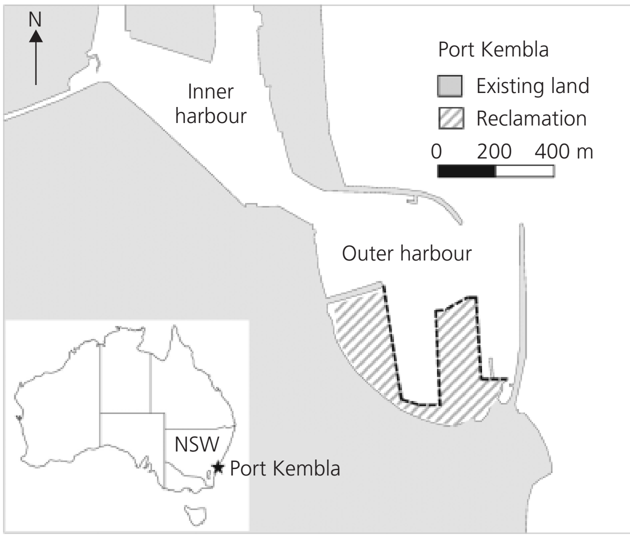


Figure 1. Layout of Port Kembla expansion project

may reduce drastically due to significant post-compaction particle breakage that is likely to occur under both static and cyclic shear loads. Alternatively, although BOS alone may possess good strength properties (e.g. Malasavage *et al.*, 2012), its long-term volumetric expansion may pose a serious limitation to its use as a stable structural fill. The use of mixtures of CW and BOS for obtaining synthetic fills having geotechnical properties similar or superior to conventional natural fills appears to be a viable option. If the favourable use of CW-BOS blend as reclamation fill material can be demonstrated, it may eventually become a sustainable and reliable practice not only in Australia, but also worldwide.

In this study, comprehensive and detailed laboratory investigations were carried out on CW, BOS and CW-BOS blends of 75/25, 50/50 and 25/75 (percentage of CW/BOS based on oven-dried weight) to evaluate their geotechnical properties, such as compaction characteristics, shear strength and bearing capacity, permeability, particle breakage and swelling (i.e. volumetric expansion). The quality and quantity of experimental data obtained from this study were crucial for identifying limitation and advantages of using CW-BOS blend. Based on this study, a framework to establish the effectiveness of granular waste fills and to optimise the CW-BOS blend as a suitable reclamation fill has been proposed for the Port Kembla outer harbour expansion.

2. Geotechnical characterisation

Typical CW and BOS samples as tested in the laboratory are shown in Figure 2. In order to identify optimum CW-BOS blends that may meet most of the geotechnical specification to be used as an effective fill for port reclamation, CW, BOS and CW-BOS blends of 75/25, 50/50 and 25/75 (percentage of CW/BOS based on oven-dried weight) were examined in the laboratory.

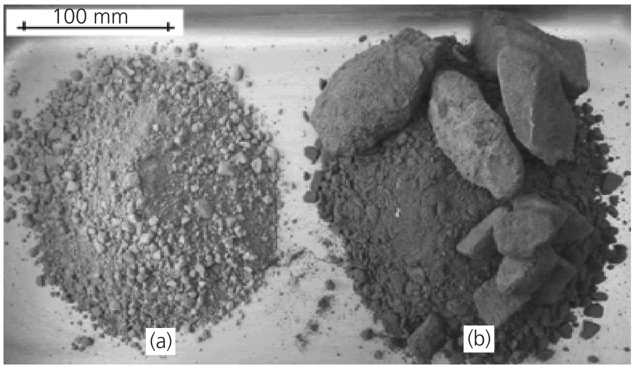


Figure 2. Typical samples of (a) BOS and (b) CW as received in the laboratory

2.1 Particle size distribution curves

Particle size distribution curves (Figure 3) were evaluated according to ASTM D6913 (ASTM, 2009a). Based on the unified soil classification system (USCS), typical CW samples can be classified as well-graded gravel with silty-sand (GW-GM). The maximum particle size of about 75–100 mm (generally sandstone or limestone pieces) reflects the mining and processing machinery. The CW fines (75 μm) are generally very low to non-plastic. Because of adhesion between fine and coarse particles, gradation of CW was better determined by using the wet sieve method. BOS samples can be classified as well-graded sand (SW) with low plasticity fines.

2.2 Specific gravity

Specific gravity (G_s) was determined as specified in ASTM D854 (ASTM, 2010a), using a vacuum system for removing entrapped air in the soil slurry and kerosene ($G_s = 0{\cdot}82$) as wetting agent for oven-dried soil.

The average G_s value for tested CW was 2·16. This relatively low value is the result of a combination of factors, including

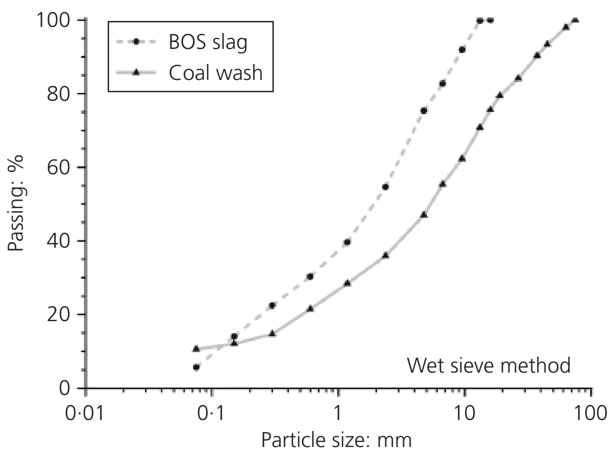


Figure 3. Particle size distribution for CW and BOS samples as received in the laboratory

mineralogical composition and the presence of coal residuals ($G_s = 1{\cdot}3$). By adding BOS to CW, it appears that the G_s increases almost linearly up to a value of 3·29 for pure BOS. This is due to the presence of iron in BOS particles. Compared to conventional (quartz-dominant) fill materials ($G_s = 2{\cdot}5$–$2{\cdot}7$), CW is lighter whereas BOS is heavier. For completeness, the average G_s values measured for CW-BOS blend are reported in Table 1 and Figure 4.

2.3 Compaction characteristics

The compactability was evaluated based on standard Proctor compaction method (ASTM D698; ASTM (2012)). To reduce the size and boundary effect, only particle sizes less than 9·5 mm were used for the tests. The material in excess of 9·5 mm was broken to smaller size grains and added as the finer fraction. Compaction tests were carried out over a broad range of moisture contents (i.e. 5–15%).

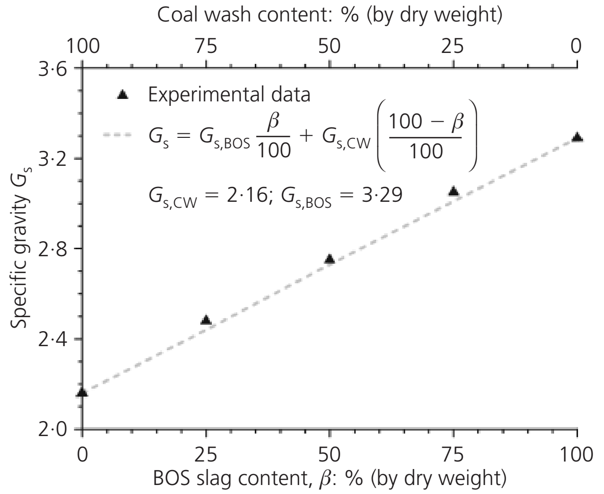


Figure 4. Specific gravity for CW-BOS blends

The variation of dry density against the moisture content at compaction for different CW-BOS blends is shown in Figure 5 and also reported in Table 1. As the BOS content increases from 0 to 100%, maximum dry density (MDD) increases from 17·2 to 22·9 kN/m^3, as well as the optimum moisture content (OMC) slightly increase from 9·8 to 12·0%. It is noted that the MDD of CW-BOS 50/50, having $G_s = 2{\cdot}73$, is comparable with those of most compacted natural fills having $G_s = 2{\cdot}65$–$2{\cdot}7$. From a practical point of view, a lower dry density is advantageous when these wastes would be used as backfill behind retaining walls, since the pressure exerted on the retaining structure as well as on the foundation structure can be less.

Previous studies (e.g. Indraratna *et al.*, 1994; Rujikiatkamjorn *et al.*, 2013) have indicated that due to the variation in specific gravity of waste materials compared to conventional natural earth-fills, the compaction effectiveness of waste materials may be better judged by the final void ratio after compaction. In Figure 6 the experimental data are plotted in terms of moisture content–void ratio relationships, and it can be seen that void ratio at MDD increases with an increase in BOS content. In the case of CW the void ratio at MDD is 0·24 (corresponding porosity of 19%), whereas for BOS the void ratio at MDD is 0·41 (corresponding porosity of 29%). These results clearly show that using the same amount of energy (i.e. 600 kJ/m^3), CW can be compacted to a lower void ratio in comparison with BOS.

The relatively low value of void ratio at MDD for CW can be attributed to its relatively small specific gravity ($G_s = 2{\cdot}16$) in comparison with a conventional fill. In fact, for a clayey or sandy soil having a $G_s = 2{\cdot}65$, a MDD of 17·2 kN/m^3 would correspond to a void ratio of 0·51 (porosity of 34%). In the same way, compared to conventional fills, the relatively high void ratio at MDD for BOS can be attributed to its higher specific gravity ($G_s = 3{\cdot}29$). For a natural soil ($G_s = 2{\cdot}65$–$2{\cdot}70$), a MDD of 22·9 kN/m^3 would correspond to a void ratio of 0·14 (porosity of 12%).

The difference in compaction properties especially dry density between these two waste materials can be partially attributed to their significantly different specific gravities. However, the much coarser and heterogeneous nature of CW compacted to BOS

Material	MDD: kN/m	Void ratio at MDD	OMC: %	G_s: (–)	k: cm/s FH	k: cm/s CH
CW	17·2	0·238	9·8	2·16	$5{\cdot}0 \times 10^{-7}$	N/A
CW-BOS 75/25	18·3	0·317	10·7	2·48	$6{\cdot}2 \times 10^{-6}$	$5{\cdot}4 \times 10^{-6}$
CW-BOS 50/50	19·8	0·359	12·0	2·75	$2{\cdot}1 \times 10^{-5}$	$2{\cdot}0 \times 10^{-5}$
CW-BOS 25/75	21·3	0·391	12·0	3·05	$3{\cdot}6 \times 10^{-5}$	$3{\cdot}9 \times 10^{-5}$
BOS	22·9	0·412	11·6	3·29	$5{\cdot}1 \times 10^{-5}$	$4{\cdot}5 \times 10^{-5}$

MDD and OMC, maximum dry density and optimum moisture content from standard Proctor compaction tests; G_s, specific gravity of mixtures; k, coefficient of permeability; FH, falling head permeability test; CH, constant head permeability test; N/A, data not available.

Table 1. Compaction characteristics, specific gravity and permeability coefficient for CW, BOS and CW-BOS blends

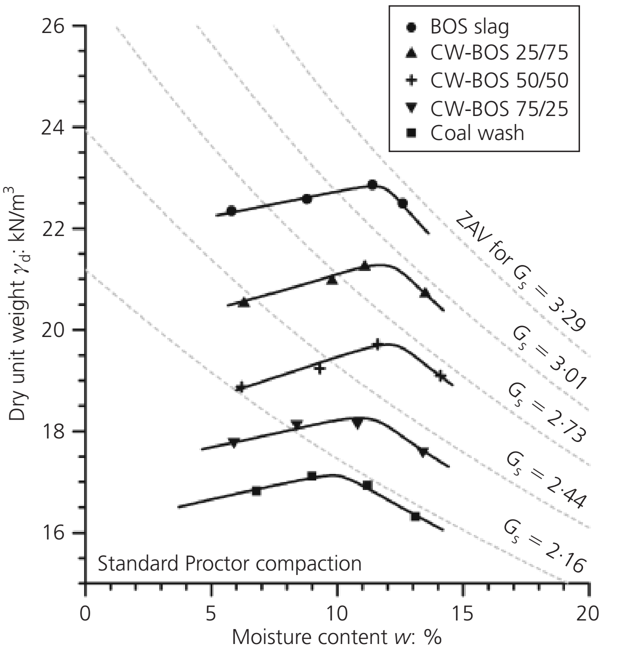


Figure 5. Standard Proctor compaction curves for CW-BOS blends

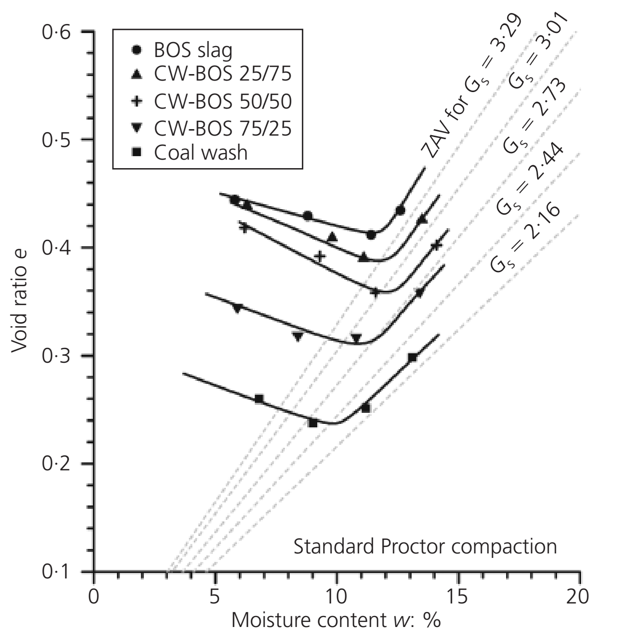


Figure 6. Moisture content-void ratio relationships for CW-BOS blends

(Figures 2 and 3) as well as significant particle breakage of CW (Rujikiatkamjorn *et al.*, 2013) would also contribute to the different compaction levels of these two waste materials.

2.4 Permeability

The permeability coefficients for BOS and 75/25, 50/50, 25/75 CW-BOS blends were evaluated at approximately 20°C room temperature by both falling-head (ASTM D5084; ASTM (2010b)) and constant-head (ASTM D2434; ASTM (2006b)) permeability tests. Falling-head permeability tests were conducted on CW specimens due to their relatively low permeability. The permeability variation for specimens compacted at their OMC is plotted in Figure 7, where the void ratios are also reported at each data point for better clarity. It is noted that both falling-head and constant-head tests provided similar results, confirming that the specimens were effectively fully saturated. Apparently, by increasing the BOS percentage from 0 to 100%, the permeability coefficient (k) decreased considerably from $5{\cdot}1 \times 10^{-5}$ cm/s (similar to sandy fills) to $5{\cdot}0 \times 10^{-7}$ cm/s (similar to clayey fills). It is evident that the decrease in k is a direct consequence of the decrease in void ratio with an increase in BOS percentage. In the case of port reclamation, a moderate permeability (1×10^{-6} cm/s $\leqslant k \leqslant 1 \times 10^{-4}$ cm/s) would be preferable in order to ensure rapid excess pore pressure dissipation and to minimise internal erosion. Otherwise, a lower permeability fill ($k < 1 \times 10^{-6}$ to 10^{-7} cm/s) could be preferable to create water-front sealing zones.

2.5 Shear strength properties by triaxial compression tests

The shear strength characteristics of CW, BOS and their blends were investigated by conducting drained triaxial compression tests on fully saturated specimens (100 mm in diameter and 200 mm in height), isotropically consolidated at a confining pressure (σ_c') of 30 and 120 kPa (to simulate the critical case expected at Port Kembla for the lowermost fill layer; that is, pressure approximately equivalent to 10 m layer of compacted fill and 60 kPa live load, or 5 m layer of compacted fill and 120 kPa live load). A strain rate of 0·2 mm/min was applied in order to ensure fully drained conditions. The specimens were prepared to a degree of compaction of 90–95% of MDD to replicate field conditions.

Figures 8 and 9 illustrate typical stress–strain and volumetric strain behaviours for $\sigma_c' = 30$ and 120 kPa, respectively. It was

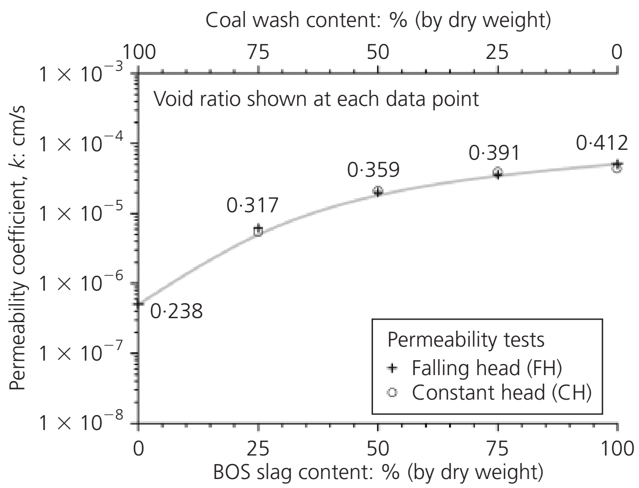


Figure 7. Permeability coefficients for CW-BOS blends

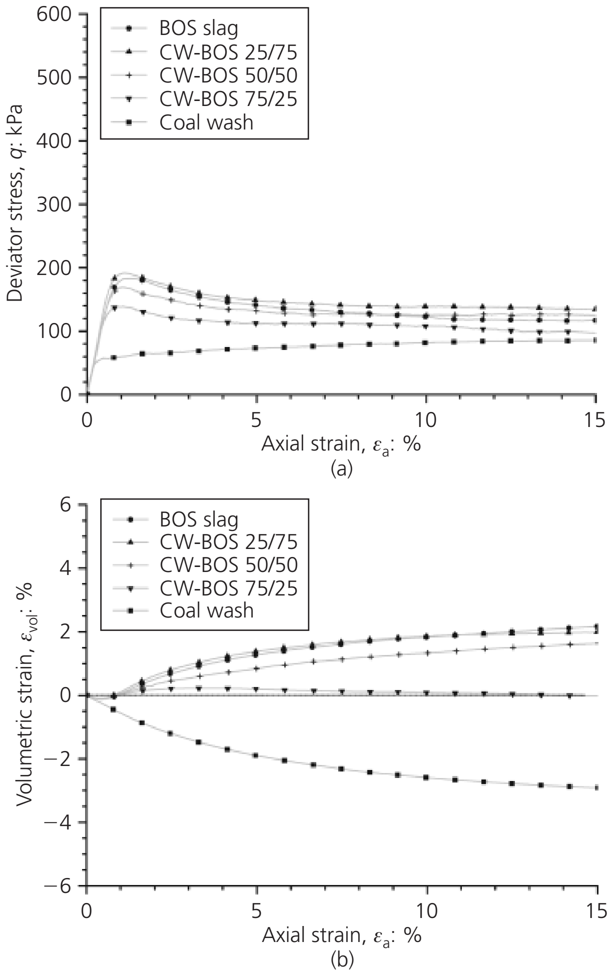


Figure 8. Consolidated drained triaxial compression test results ($\sigma_c' = 30$ kPa): (a) stress–strain relationships; (b) volumetric strain behaviours

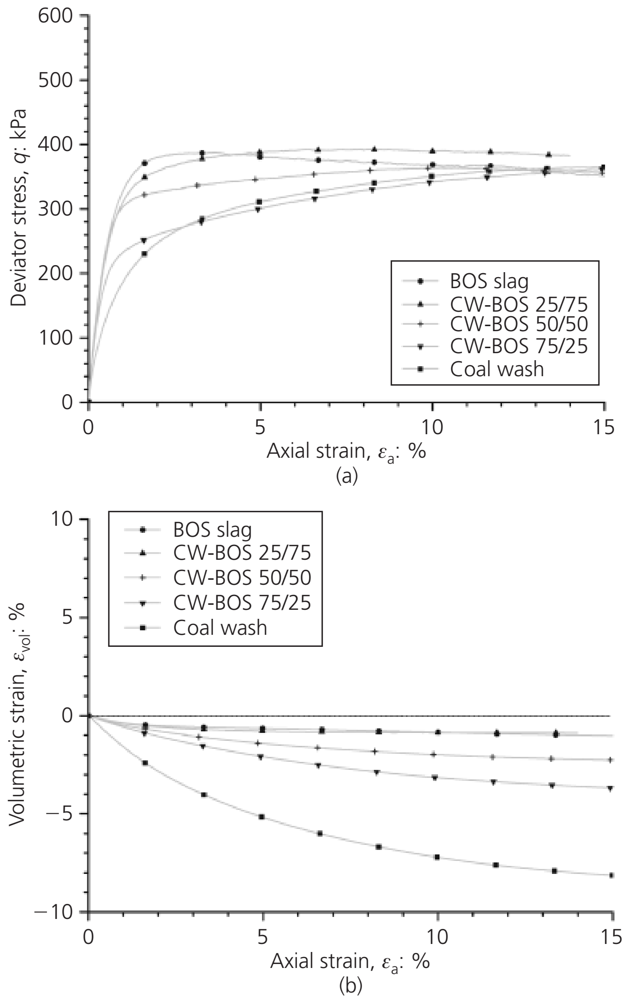


Figure 9. Consolidated drained triaxial compression test results ($\sigma_c' = 120$ kPa): (a) stress–strain relationships; (b) volumetric strain behaviours

observed that under a relatively low confining pressure of $\sigma_c' = 30$ kPa, except for CW, all the tested materials show a dilative response, and the peak stress was followed by strain softening. In contrast, at a higher confining pressure of $\sigma_c' = 120$ kPa, the deviator stress increased monotonically and all specimens showed a contractive behaviour. As expected, the pure CW specimen was the most contractive.

The friction angle measured at the peak deviator stress (ϕ'_{peak}) and its variation with BOS content is shown in Figure 10 and reported in Table 2. At lower confining pressure, BOS and the blended materials sustained an increased friction angle (46–48°), proving substantial particle interlocking compared to the pure CW. At higher confining pressure of $\sigma_c' = 120$ kPa, all specimens showed a similar friction angle of $\phi'_{peak} = 36–38°$ as dilation was suppressed. Nevertheless, these values are still similar or higher than those typically expected for conventional fills ($\phi'_{peak} =$ 34–38°; Hausmann, 1990). In brief, in view of interparticle friction, the blended CW-BOS specimens can provide a higher shear strength than most sandy fills of similar grain sizes.

2.6 Bearing capacity by California bearing ratio tests

As potential subgrade materials, the strength of CW, BOS and their blends was assessed using soaked and unsoaked California bearing ratio (CBR) tests (ASTM D1883; ASTM (2006a)) on specimens compacted at their OMC, while using a plunger of diameter 50 mm to penetrate the specimens at a constant rate of 1mm/min. Figure 11 shows the typical pressure–vertical strain relationship obtained from unsoaked specimens, together with the corresponding resilient modulus ($M_R = d\sigma_y/d\varepsilon_y$). These results indicate that BOS is the most resistant material having an M_R exceeding 80 MPa. In comparison, CW appeared to provide the least resistance with its M_R just above 20 MPa. In Figure 12, soaked and unsoaked CBR values measured at a penetration of 5·08 mm are shown for all specimens. The range of CBR value varies from 10% (CW) to 40% (BOS) for the unsoaked tests and

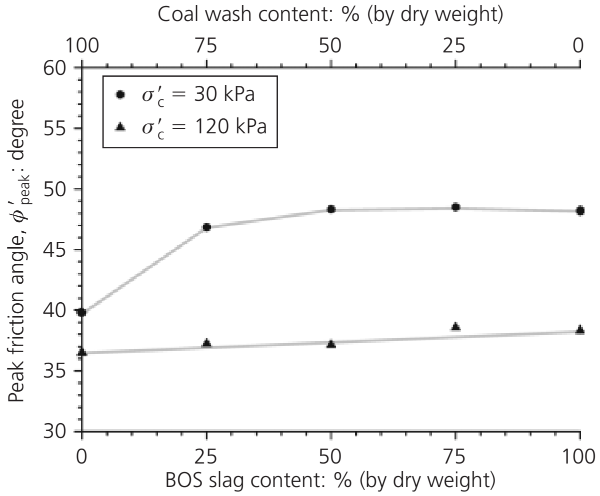


Figure 10. Peak friction angles for CW-BOS blends

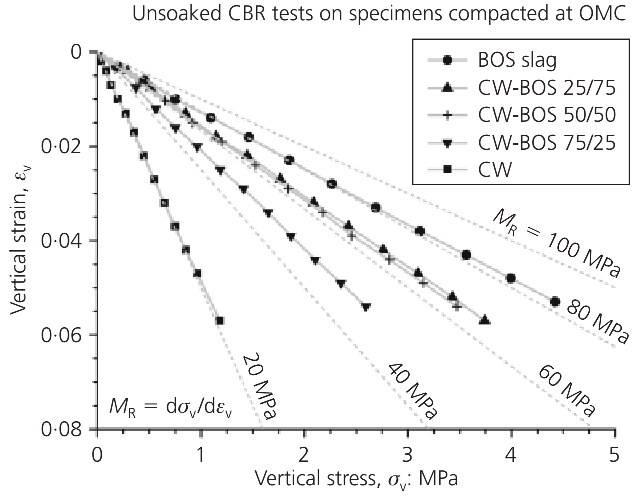


Figure 11. Settlement–pressure relationships from unsoaked CBR tests for CW-BOS blends

Material	ϕ'_{peak}: ° @ σ'_c = 30 kPa	ϕ'_{peak}: ° @ σ'_c = 120 kPa	CBR: % soaked	CBR: % unsoaked
CW	39·2	36·5	7·8	10·1
CW-BOS 75/25	46·8	37·2	18·2	23·6
CW-BOS 50/50	48·3	37·1	24·3	31·5
CW-BOS 25/75	48·5	38·6	24·9	32·4
BOS	48·2	38·3	31·3	40·7

ϕ'_{peak}, friction angle at peak deviator shear state; CBR, California bearing ratio; σ'_c confining pressure.

Table 2. Shear strength and CBR values for CW, SFS and CW-SFS blends

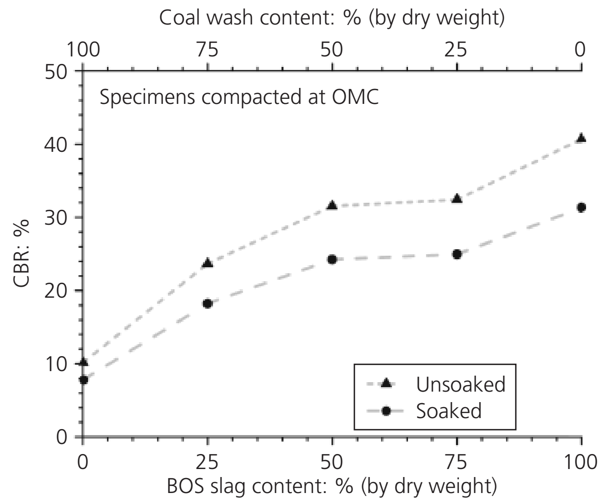


Figure 12. CBR characteristics for CW-BOS blends

from 7·8% (CW) to 31% (BOS) for the soaked tests. For both unsoaked and soaked tests, CBR decreases significantly with increasing CW content, and this is mainly due to the higher crushability of CW particles compared to BOS grains. Moreover, as expected, CBR values for soaked specimen are less than those of unsoaked specimens, as unsoaked compacted specimen sustain a greater suction (unsaturated). With the exception of the case of soaked CW specimens, the CBR values obtained in this study were generally similar to those typical of sandy soils (i.e. CBR = 10–40%; Hausmann, 1990).

2.7 Particle breakage

Evaluation of particle breakage is essential to understand the level of degradation that a granular material undergoes when subject to impact loading (e.g. compaction by drop-weight) and shearing under monotonic and cyclic loading conditions, and it can be quantified by means of the breakage index (BI; Indraratna *et al.*, 2005). In this study, BI was measured for different CW-BOS blends, and the extent of particle breakage was defined just after compaction at OMC, and more importantly after the application of subsequent static shearing under confining pressures of 30 and 120 kPa.

Figure 13(a) shows the post-compaction particle size distribution (PSD) curve compared with the initial PSD curve for CW-BOS 50/50 specimens. During compaction and subsequent shearing, some particle degradation occurs, thereby causing a shift in the initial PSD to the left (i.e. towards smaller particle sizes). It is assumed that, the maximum particle size remains unchanged before and after compaction. This shift in the PSD curve represents an area A (Figure 13(a)). The higher the breakage of grains, the greater the PSD shift from its original position (i.e. the area A). The area B represents the potential breakage defined

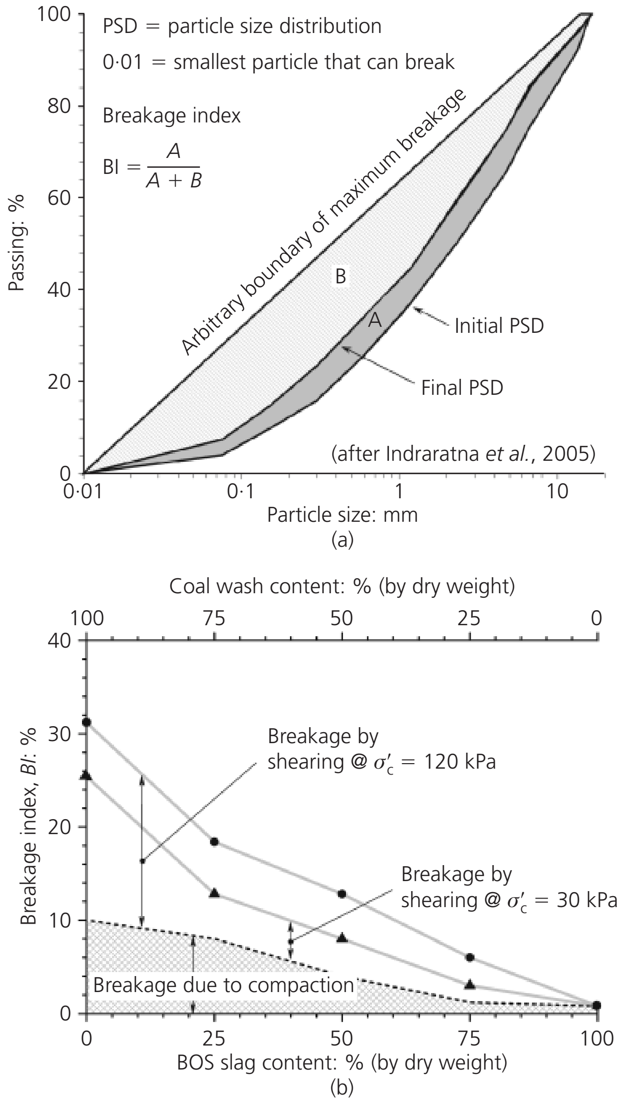


Figure 13. (a) Breakage index (modified after Indraratna *et al.*, 2005); (b) particle breakage induced by compaction and shearing at a σ_c' of 30 and 120 kPa

by the area between the arbitrary boundary of maximum breakage and the final PSD (Figure 13(a)). The breakage index (BI) is defined as follows (after Indraratna *et al.*, 2005):

$$\mathrm{BI} = \frac{\mathrm{A}}{\mathrm{A} + \mathrm{B}}$$

As expected, post-compaction particle breakage (Figure 13(b)) was moderate for CW (BI = 10%), whereas negligible for BOS particles (BI = 0·8%). This is because the more fragile nature and angular shape of CW particles compared to the more rounded and resistant BOS grains. Remarkably, the particle breakage measured after shearing under a $\sigma_c' = 30$ kPa was still important for CW (BI = 15·2%), while it was relatively insignificant for BOS (BI = 0·2%). It also appears that, the majority of particle breakage under shearing occurs at low confining pressure. In fact, an increase in σ_c' up to 120 kPa will only produce an additional BI of about 5%, except for the case of pure BOS, for which BI = 0·2%

For this analysis, it is clear that post-compaction particle breakage of CW cannot be neglected. However, the addition of BOS to CW will significantly reduce particle breakage of compacted fill subjected to shearing and thus the level of deformation in the field under live loading conditions. This is because BOS particles not only are much stronger against breakage, but by filling the voids between coarser CW particles they also act as a shelter to CW particles.

2.8 Swelling (volumetric expansion) behaviour

Figure 14 reports the free-swell behaviour (i.e. no pressure is applied on the top of specimen) measured in the laboratory by one-dimensional (vertical direction only) expansion tests, using a hot water bath (70°C; ASTM D4792; ASTM (2006c)). Swelling under ambient temperature may continue over a long period of time, often exceeding a year. Therefore, the test using a hot water bath was chosen to accelerate the swelling process and to provide an indication of the maximum amount of volumetric expansion to be expected in the field. A significant volumetric expansion of about 8% could be observed for BOS after 40 d. This behaviour can be associated with the hydration of free lime (CaO) and free magnesium (MgO) to form calcium hydroxide ($Ca(OH)_2$) and magnesium hydroxide ($Mg(OH)_2$). Alternatively, no swelling but shrinkage was observed for CW.

These tests clearly show that swelling is one of the most crucial factors in the evaluation of waste material to be used as a structural fill for port reclamation. Especially for BOS, swelling

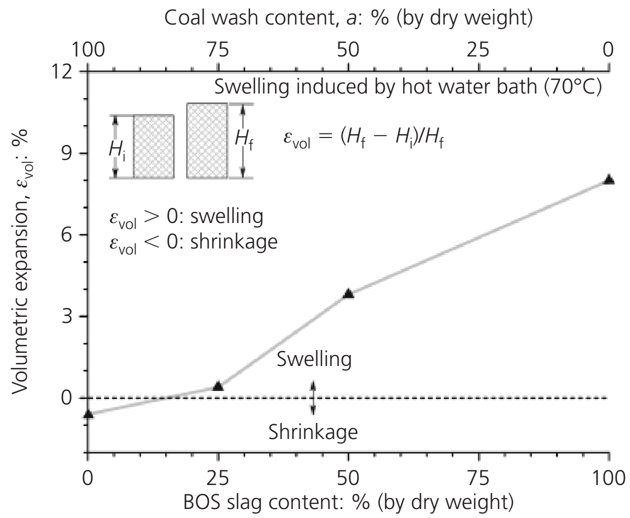


Figure 14. Swelling properties for CW-BOS blends

cannot be neglected. In fact, such large volumetric expansion is likely to induce major differential settlement that can cause damage to buildings, transport systems and other infrastructure built on the compacted fill as well as to utility systems buried within compacted fill (e.g. water and severe pipelines, telecommunication systems etc.). However, for CW-BOS blends the swelling is drastically reduced, enabling their adoption as fill materials.

3. Proposed acceptance criteria for granular waste fills

For conventional sandy soil, design criteria based on frictional shear strength, bearing capacity and permeability are used to assess their suitability as structural fill material for port reclamation. It is often required that fills should possess a friction angle greater than or equal to 30° (Davies and McIlquam, 2011) and/or a CBR $> 10\%$, to guarantee a satisfactory shear resistance and to minimise post-construction settlement. In addition, it is also recommended that fill material should have a permeability coefficient similar to that of sandy fills (i.e. 1×10^{-6} cm/s $< k < 1 \times 10^{-4}$ cm/s) to ensure rapid dissipation of excess pore water pressure and to minimise internal erosion.

In view of key factors identified in this study, such as swelling and particle breakage characteristics, design criteria merely based on strength and permeability may be insufficient to fully judge whether or not a granular waste material meets all the geotechnical requirements to be used as an acceptable structural fill for reclamation. To overcome this difficulty, a modified framework with comprehensive design criteria, including four levels of acceptance, is proposed (Figure 15).

- *Level 1: Frictional shear resistance and/or bearing capacity.* Structural fill should possess adequate shear strength and bearing capacity to guarantee a satisfactory shear resistance and reduced post-construction settlement. Similar to conventional sandy fills, waste materials when used as structural fills should also have a friction angle $\phi' > 30°$ and/or a CBR $> 10\%$. Otherwise, they could only be recommended as general fills.
- *Level 2: Swelling (volumetric expansion).* This is the most crucial level, as swelling may continue for a long period of time. It is suggested that waste material be accepted as structural fill only if swelling is $< 3\%$, unless the applied live load should exceeds the swell pressure.
- *Level 3: Post-compaction particle breakage.* Particle breakage is a good indicator of level of deformation to be expected in the field for compacted fill material. In the case of waste materials, even if the shear resistance is adequate, the post-compaction particle breakage may not be acceptable. Therefore, in the case of structural fills, it is suggested that BI $< 10\%$ at a reference confining pressure of 120 kPa. Otherwise, they could be simply adopted as a general fill.
- *Level 4: Design criterion based on permeability.* In order to guarantee rapid dissipation of excess pore water pressure (i.e. maintaining relatively free-draining), it is recommended that structural fills should have a permeability coefficient similar to that of sandy fills (i.e. 1×10^{-6} cm/s $\leqslant k \leqslant$

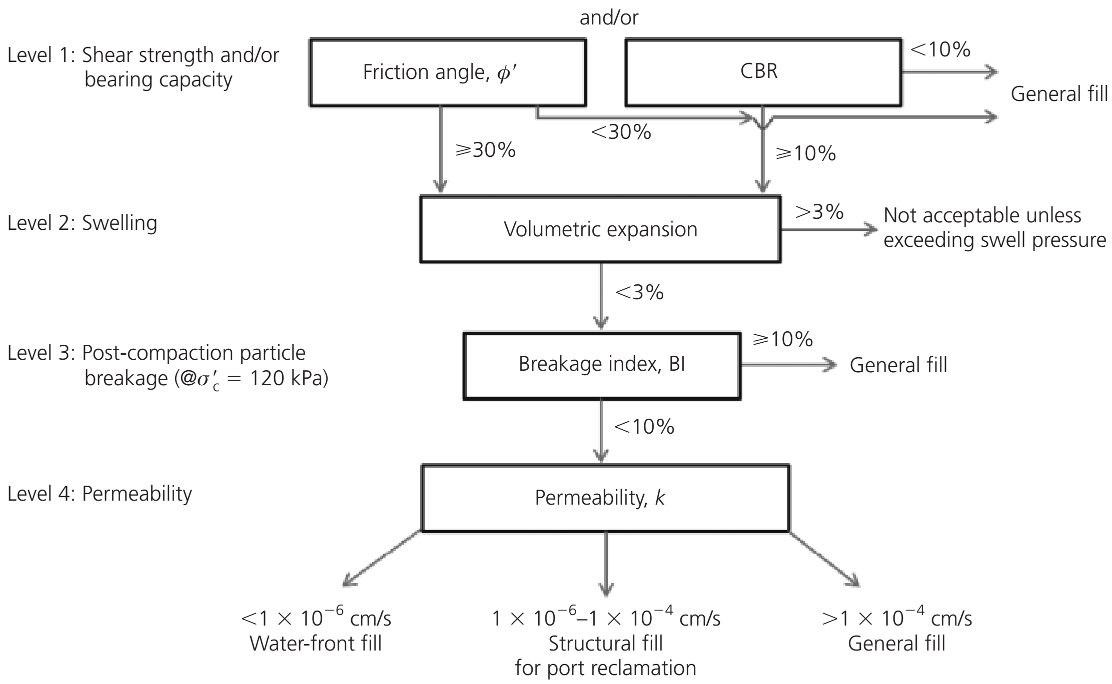


Figure 15. Proposed acceptance criteria for CW-BOS blends as structural fills

1×10^{-4} cm/s). However, when $k < 1 \times 10^{-6}$ cm/s, this material could still be used as a water front low permeability fill (e.g. surface water retention bund). If $k > 1 \times 10^{-4}$ cm/s, these waste materials could be used as general fills.

4. Optimisation of coal wash–BOS slag fines blend

As shown in Figure 16, using the proposed design criteria, optimisation of CW-BOS blend as potential structural fill material for port reclamation was conducted. It was found that while all the tested material satisfied the acceptance criteria based on friction angle ($\phi' > 30°$) and bearing capacity (CBR > 10%), only the mixture with a BOS content less than 45% would ensure a swelling (volumetric expansion) < 3%. However, breakage index (BI) indicated that when BOS content was less than 25%, the level of particle breakage due to shearing would be substantial (i.e. BI > 10%). Consequently, optimum CW-BOS blends are those in the range of CW-BOS 70/30 and CW-BOS 55/45. For such materials, acceptance based on permeability is also fulfilled (i.e. k is between $6{\cdot}9 \times 10^{-6}$ cm/s and $1{\cdot}5 \times 10^{-5}$ cm/s).

5. Practical applications

In September 2012, a field trial was carried out at Port Kembla reclamation site to evaluate the in situ performance of two selected CW-BOS blends and to establish a suitable compaction method for CW-BOS fills. It is important to mention that, at the request of PKPC, the two blends were initially selected based only on strength and permeability properties, as at that time the roles of swelling and particle breakage were not completely established. Nevertheless, the field trial was an essential part of this investigation to properly measure in situ swelling and to understand the advantages and limitations of using CW-BOS blends as compacted fill material.

An area with dimensions of 55 m length, 14 m width and 1·4 m depth was provided by PKPC for the field trial. The area was divided in two equal parts having a volume of approximately 540 m^3 and filled by CW-BOS 43/57 (50/50 by volume) and CW-BOS 27/73 (33/67 by volume). Approximately 1200 t of CW and 1600 t of BOS were used. The blending operations were accomplished by using an excavator (lifting and mixing operation), a dumper truck (transporting and dumping operation) and a road grader (spreading and levelling operation). However, if a large amount of material had to be mixed, then the use of a twin-shaft pugmill would be desirable (Malasavage *et al.*, 2012). Compaction of 300 mm thick layers was completed by means of 13 t smooth steel drum rollers (Figure 17). Based on a number of field density tests, such as the sand cone replacement and nuclear density techniques, it was found that four passes were adequate for achieving a fill density > 90% standard Proctor compaction. Dynamic cone penetration tests (ASTM D6951; ASTM (2009b)) confirmed that compacted CW-BOS fills have greater strength compared to compacted sandy fill. As shown in Figure 18, for both tested CW-BOS blends the number of blows to penetrate 100 mm is greater than 10, which is a reference value for dense sandy soils.

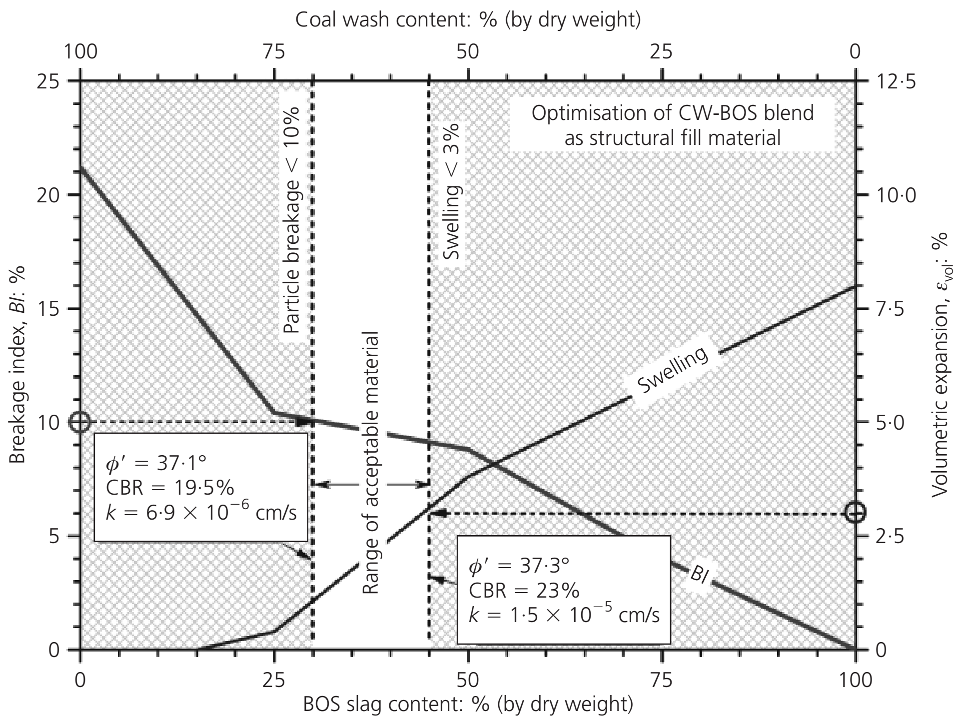
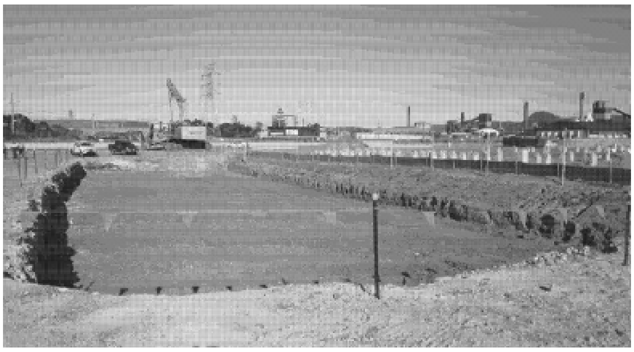


Figure 16. Optimisation of CW-BOS blend as structural fill material for port reclamation



(a)

(b)

Figure 17. Port Kembla construction site: (a) prior to fill placement and (b) during compaction

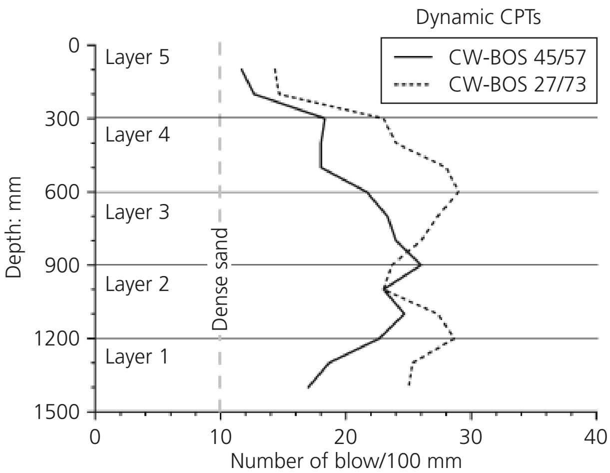


Figure 18. Dynamic cone penetration tests conducted 1 week of after compaction

Volumetric expansion was also surveyed for a period of about 6 months. As shown in Figure 19, swelling was found to be substantial for both of the blends. On the basis of this field trial and further laboratory investigations, it was agreed that although the strength of CW-BOS blend with BOS content $> 50\%$ may be better in comparison with most sandy soils, such significant level of swelling (i.e. $> 3\%$) should not be readily accepted for CW-BOS blend when used as structural fill, unless the live load exceeds the swell pressure (about 100 kPa for BOS).

6. Conclusions and recommendations

Comprehensive laboratory and field investigations were conducted to explore the potential of using a CW-BOS blend as structural fill for the Port Kembla Outer Harbour reclamation near Wollongong City, Australia. The following salient findings were obtained.

(*a*) Increasing confining pressure from 30 to 120 kPa (critical pressure expected at Port Kembla) causes the peak friction angle (ϕ'_{peak}) to decrease from 40–48° to 36–38°, as dilation is suppressed at higher confining pressure. Nevertheless, these values are still similar to or higher than those typically expected for conventional fills ($\phi'_{\text{peak}} = 34$–38°).
(*b*) Except for the soaked CW specimen, CBR values for CW-BOS blends were generally similar to typical sandy fills (i.e. CBR = 10–40%).
(*c*) With the exception of the CW specimen, CW-BOS blends usually have a moderate permeability (1×10^{-6} cm/s $\leqslant k \leqslant 1 \times 10^{-4}$ cm/s), which is sufficient to ensure rapid excess pore pressure dissipation.
(*d*) Post-compaction particle breakage of CW cannot be neglected (i.e. BI $> 10\%$). However, the addition of BOS to CW will significantly reduce particle breakage under static shearing.
(*e*) Swelling of BOS ($> 3\%$) was found to be a critical factor. Under ambient temperature it may continue over a long period of time, often exceeding a year, and may initiate significant differential settlement and damage to port infrastructure. However, by adding CW to BOS, the swelling can be controlled to acceptable levels.

In summary, while CW-BOS fills have shear resistance, bearing capacity and permeability properties similar or superior to conventional sandy fills, their use may still be restricted by excessive swelling and/or particle breakage. Consequently, the acceptance criteria merely based on shear strength and permeability may not be sufficient to fully judge whether or not such a granular waste blend meets all the requirements for an acceptable reclamation fill. For the case study presented here, only CW-BOS blends with a BOS content between 30 and 45% are able to meet the stringent port reclamation specifications, in terms of swelling ($< 3\%$) and particle breakage (BI $< 10\%$).

It is important to note that the results presented in this paper are only indicative and not necessarily applicable to all types of CW-BOS blends, because the geotechnical properties of such wastes can vary significantly, depending on the chemical contents of the materials, the original source and manufacturing processes. Therefore, caution should be exercised in extrapolating the results of this study. For this reason, it is strongly recommended to carry out field

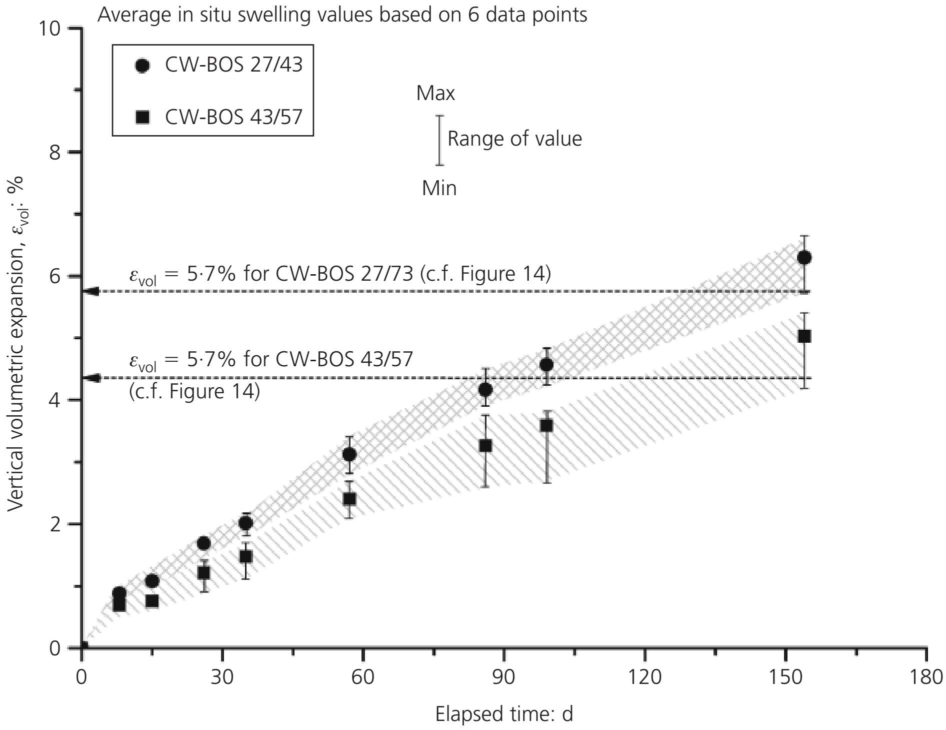


Figure 19. In situ swelling behaviour of CW-BOS blend

trials with live load application and additional in situ investigations to verify the actual performance of CW-BOS blends.

In order to provide a more comprehensive geotechnical description of CW-BOS blends and derive more solid conclusions that can be widely used by industry, further works are currently being undertaken. Due to the heterogeneity of these materials as well as the complexity of loading conditions in the field, the adoption of such compacted granular waste materials as suitable structural fills will be supported by the development of a comprehensive constitutive model capable of properly describing the stress–strain behaviour of these materials under representative port loading conditions.

Further recommendations for future work include investigating the mechanical response of CW-BOS blends under cyclic triaxial shearing conditions, focusing on the breakage characteristics, since in situ soils are frequently subjected to cyclic loadings. In addition, if such waste materials are used in areas susceptible to earthquake ground shakings, undrained cyclic tests should be carried out to evaluate pore water pressure generation properties and liquefaction potential.

Finally, as coal wash and BOS slag are both dual porosity materials, further studies based on computed tomography and scanning electron microscopy will need to be undertaken to investigate their structural changes under high cyclic loading, especially during saturated and undrained loading that leads to complex effective stress conditions.

Acknowledgements

This study was undertaken under an industry linkage project funded by the Australian Research Council. The authors wish to acknowledge the industrial partners Port Kembla Port Corporation, Coffey Geotechnics, Douglas Partners, Menard Bachy, BHP Billiton-Illawarra Coal and Australian Steel Mill Services. Laboratory assistance by Michael Lofts, Jordan Peterson and Ian Laird, and the field assistance by provided Dr Ana Heitor, Chazath Kaliboullah and Fernando Escribano are gratefully appreciated.

REFERENCES

ASTM (American Society of Testing and Materials) (2006a) D1883: Standard test method for CBR (California Bearing Ratio) of laboratory-compacted soils. ASTM International, West Conshohocken, PA, USA.

ASTM (2006b) D2434: Standard test method for permeability of granular soils (constant head). ASTM International, West Conshohocken, PA, USA.

ASTM (2006c) D4792: Standard test method for potential expansion of aggregates from hydration reactions. ASTM International, West Conshohocken, PA, USA.

ASTM (2009a) D6913: Standard test methods for particle-size distribution (gradation) of soils using sieve analysis. ASTM International, West Conshohocken, PA, USA.

ASTM (2009b) D6951/D6951M: Standard test method for use of the dynamic cone penetrometer in shallow pavement applications. ASTM International, West Conshohocken, PA, USA.

ASTM (2010a) D854: Standard test methods for specific gravity of soil solids by water pycnometer. ASTM International, West Conshohocken, PA, USA.

ASTM (2010b) D5084: Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter. ASTM International, West Conshohocken, PA, USA.

ASTM (2012) D698: Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM International, West Conshohocken, PA, USA.

Davies PRE and McIlquam JD (2011) Geotechnical design for the Port Botany expansion project, Sydney. *Geotechnical Engineering* **164(GE3)**: 149–167.

Hausmann MR (1990) *Engineering Principles of Ground Modification*. McGraw-Hill, New York, USA.

Indraratna B, Gasson I and Chowdury RN (1994) Utilization of compacted coal tailings as a structural fill. *Canadian Geotechnical Journal* **31(5)**: 614–623.

Indraratna B, Lackenby J and Christie D (2005) Effects of confining pressure on the degradation of ballast under cyclic loading. *Geotechnique* **55(4)**: 325–328.

Lai Z, His J, Rheinberger T and Andrews T (2011) Geotechnical offshore site investigation and reclamation design at Port Kembla. *Proceedings of Australian Geomechanics Society Sydney Symposium, Coastal and Marine Geotechnics: Foundations and Trade, Sydney, Australia*, pp. 61–72.

Malasavage NE, Jagupilla S, Grubb DG, Wazne M and Coon WP (2012) Geotechnical performance of dredged material-steel slag fines blends: laboratory and field evaluation. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **138(8)**: 981–991.

Okabue CO and Ochulor OH (2007) The potential of cemented-stabilized coal-reject as construction material. *Bulletin of Engineering Geology and the Environment* **15(2)**: 143–151.

Rujikiatkamjorn C, Indraratna B and Chiaro G (2013) Compaction of coal wash to optimize its utilization as water-front reclamation fill. *Geomechanics Geoengineering: an International Journal* **8(1)**: 36–45.